COMPARISON OF ACTUAL AND SIMULATED WATER QUALITY RESPONSES TO PHOSPHORUS LOADING SCENARIOS IN LAKE ONTARIO AND LAKE ERIE

By

W.M. Schertzer[1] and R. Stevens[2]

[1]Aquatic Physics and Systems Division
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario, Canada L7R 4A6

[2]Water Quality Branch,
Ontario Region
Burlington, Ontario, Canada

COMPARISON OF ACTUAL AND SIMULATED WATER QUALITY RESPONSES TO PHOSPHORUS LOADING SCENARIOS IN LAKE ONTARIO AND LAKE ERIE

By

W.M. Schertzer[1] and R. Stevens[2]

[1]Aquatic Physics & Systems Division

National Water Research Institute, Burlington, Ontario

[2]Water Quality Branch, Ontario Region, Burlington, Ontario

ABSTRACT

Water quality models developed at the Canada Centre for Inland Waters are used to simulate the effect of various phosphorus loading scenarios in Lake Ontario and Lake Erie. Simulation results are compared to actual conditions resulting from the institution of phosphorus remedial measures.

In Lake Ontario the maximum and minimum trends in epilimnion SRP, OP and TP concentrations are outlined for hypothetical phosphorus loading changes ranging from -50 to +50% in the period 1972 to 1983. Assuming a +10% loading change in this period, a difference in the simulated maximum TP epilimnion concentration in year 1983 is as much as 10 µg/L higher than the results representative of current values attributable to the program of phosphorus loading abatement (about -50% change).

In Lake Erie the effect of a constant total phosphorus loading in the period 1967 to 1982 was contrasted against water quality responses using actual total phosphorus loading reductions. A measure of the difference was expressed in terms of the 'prevalence' of anoxia occurrence. Cumulation of simulated hypolimnion volumes over the period of anoxia (oxygen concentration < 1.5 mg/L) dramatically illustrates that the effect of remedial measures has been to substantially reduce the 'prevalence' of anoxia in comparison to scenarios without phosphorus reduction.

INTRODUCTION

Eutrophication of the Lower Great Lakes was demonstrated to be related to nutrient enrichment. The consequences of such artificial enrichment included the proliferation of aquatic weeds such as cladophora and the occurrence of anoxia especially in the Central Basin of Lake Erie. Total phosphorus was determined as the nutrient responsible for the continued enrichment (Burns and Ross, 1972) and in an effort to reduce the water quality problems in the lakes, a phosphorus loading reduction program was instituted in Canada and the United States (IJC, 1978). The program was fully initiated in 1972 and included such measures as reductions of phosphates in detergents and introduction of secondary sewage treatment.

The phosphorus reduction program has been in effect for approximately 12 years and observations have shown decreases in concentrations within the lakes. The following discussion details a comparison of actual and simulated water quality responses to various scenarios of total phosphorus loading changes for Lake Ontario and Lake Erie. Water quality models are used to derive simulations of the trends in concentration in response to specified loading changes.

WATER QUALITY MODEL

The water quality models used to simulate the effects of total phosphorus loading changes in Lake Ontario (Simons, 1978) and in Lake Erie (Lam, Schertzer and Fraser, 1983) are illustrated schematically in Figure 1. In general, the Lake Ontario model is a two-layer system (epilimnion and hypolimnion) in which a physical system and chemical processes are incorporated to effect a mass balance of SRP and OP between compartments. The Lake Erie model is similar in concept to the Lake Ontario model except that a third compartment representing a transition zone (i.e. mesolimnion) is included as well as a third component which is dissolved oxygen.

An example of the application of the water quality model for Lake Erie is given in Figure 2. Simulation of the seasonal cycle of West Basin epilimnion total phosphorus concentrations and the Central Basin hypolimnion dissolved oxygen concentration show good correspondence with measured values. Additional simulations for temperature, SRP, TP and dissolved oxygen for epilimnion, mesolimnion and hypolimnion layers is shown in (Lam, Schertzer and Fraser, 1983).

SIMULATION OF ACTUAL PHOSPHORUS CONCENTRATIONS

Actual total phosphorus loadings to Lake Ontario and Lake Erie are given in Figure 3 and 6 for the years 1967 to 1972 (Fraser and

Willson, 1981; Lam et al, 1983). Simulation of the Lake Ontario epilimnion phosphorus concentrations proceeds by initializing the water quality model. Using the 1972 TP loading value and initial specification of the epilmnion and hypolimnion SRP and OP (OP=TP-SRP) concentrations (Neilson and Stevens, 1983) with estimates of settling and repiration rates, a simulation of the seasonal SRP and OP concentrations are possible for each layer.

Figure 4 shows a sample simulation of actual epilimnion SRP concentrations for Lake Ontario compared with observations (Neilson and Stevens, 1983). In these simulations a linear decrease in annual loading is assumed. An annual trend to the computed results is illustrated by connecting the annual maximum and minimum seasonal simulations. For most years the seasonal simulations are in good agreement with observations. In this simulation of actual epilimnion SRP concentration, the trend to decreasing maximum concentrations from 1972 to 1983 is indicative of the positive effects of the phosphorus removal program. In a large measure, some of the reductions are also due to decreased TP loadings from Lake Erie. Similar simulations of Lake Erie phosphorus concentrations are also possible (as shown in Figure 2). Again, good agreement between computed and observed results is obtained and renders us the confidence to apply the models operationally (e.g. Lam and Hansen, 1983) to hypothetical scenarios for management analyses.

SIMULATION RESULTS FOR HYPOTHETICAL TOTAL PHOSPHORUS LOADING CHANGES

Lake Ontario

As indicated previously, phosphorus remedial measures in Lake Ontario were fully implemented in 1972. For the purposes of this discussion, total phosphorus loads in 1972 (13.6 MT) are used as the initial load for input to the Lake Ontario water quality model. Figure 3 shows initial TP loading in 1972 and hypothetical TP loading changes over the period 1972 to 1983. Five hypothetical scenarios are considered which are loading changes of -50, 0, +10, +25 and +50 percent over the 12 year simulation period. All other input parameters, such as settling and respiration rates, are held constant. The results for all five scenarios are given as trends in Figure 5 for epilimnion SRP, OP and TP maximum and minimum concentrations.

The simulated trends for the case -50 percent phosphorus loading reduction (Figure 5) closely resembles the actual loading decrease as depicted in Figure 3. Consequently, the results for the other four scenarios (0, +10, +25 and +50 percent) can be compared to this result to indicate the effect of the remedial measures. In the case of TP epilimnion concentrations, a comparison of maximum concentrations for the cases of -50 and 0 percent TP loading change over the 12 year simulation period shows that in 1983 as much as 9.9 µg/L difference

would be expected. Larger differences are apparent in comparing the -50 percent result with the other scenarios. The differences in maximums for the year 1983 are (10 µg/L, +10% increase); (13 µg/L, +25% increase) and (17 µg/L, +50% increase) for the remaining scenarios. Results for epilimnion SRP and OP concentrations are also given for each scenario.

Lake Erie

In Lake Erie, a measure of the effectiveness of the phosphorus removal program is the extent of and occurrence of Central Basin anoxia. Reductions in the available nutrient total phosphorus would be expected to result in an alleviation of the anoxic problem in Lake Erie. Previous studies (Charlton, 1980; Lam, Schertzer and Fraser, 1983) have indicated that meteorological factors which influence the hypolimnion thickness also have a significant effect upon the formation of anoxia within the hypolimnion. The Lake Erie water quality model incorporates a complex physical submodel which defines the hypolimnion thickness (Figure 1b). In this discussion, we combine the results of the physical regime and the simulated dissolved oxygen from the water quality model to define how 'prevalent' anoxia is from one year to another. Since the computation of dissolved oxygen concentrations is dependent on the loadings of total phosphorus to the system, different scenarios can be tested to demonstrate the effects

of phosphorus reductions on the water quality of Lake Erie. In the discussion which follows, we consider the results as determined from actual total phosphorus loading reductions in the period 1967 to 1983 contrasted against a scenario in which there is a constant total phosphorus loading in the simulation period.

Figure 7a graphically represents the 'prevalence' of anoxia based on computed hypolimnion volume and dissolved oxygen concentrations. Cumulative anoxic volume is defined as the sum of the computed daily hypolimnion volume over the period in which hypolimnion dissolved oxygen concentration is less than 1.5 mg/L. In another calculation we attempt to normalize this value by determining the ratio between the cumulative anoxic volume and the total hypolimnion volume determined when the upper interface is greater than 19 m, terminating when the dissolved oxygen concentration is again larger than 1.5 mg/L. The depth 19 m is chosen as it relates to the mean depth of the lake and is correlated with the occurrence of anoxia (Lam and Schertzer, 1984).

Figures 7b and 7c show the 'prevalence' of anoxia in the Central Basin of Lake Erie over the period 1967 to 1982 for the actual loading reduction (shading) and for the constant loading scenario (no shading). The diagrams illustrate that the years 1967, 1969, 1970, 1974 and 1977 to 1980 have the most prevalent anoxic occurrences) over the 16 year simulations. In contrast to the results using actual loading reductions, the effect of using a constant total phosphorus

loading at a high value of 28 MT/year (Figure 6) is to increase the 'prevalence' of anoxia in the Central Basin by extending the time in which the computed dissolved oxygen concentration is less than 1.5 mg/L. Note that for the recent years (1978-1983) anoxic conditions could have been much more severe (Figure 7b and 7c) had there not been the phosphorus reduction program.

CONCLUSION

The responses of Lake Ontario and Lake Erie to phosphorus loading reduction were determined for various scenarios through simulations incorporating water quality models developed at CCIW. By accounting for physical and chemical processes, these water quality models demonstrate that simulations of seasonal concentrations in phosphorus and dissolved oxygen for various compartments is possible and that these compare well with observations. By determining the trend in computed long-term simulations for phosphorus components, a comparison of various phosphorus loading scenarios demonstrates that the phosphorus reduction programs instituted in 1972 have had a significant effect in reducing phosphorus concentrations in Lake Ontario. In the simulation period 1972 to 1983 a constant loading scenario for phosphorus to Lake Ontario in the absence of the remedial programs would have resulted in maximum TP concentrations in 1983 in the range of 9 µg/L higher than current values. In Lake Erie the adoption of a phosphorus removal program appears to have had the

effect of reducing the 'prevalence' of Central Basin anoxia. Using the two measures of the prevalence of anoxia (Figure 7a and 7b), simulations using a high constant TP loading over the period 1967 to 1983 indicate that episodes of anoxia without remedial programs were 85 to 100 percent more prevalent compared to results with the phosphorus reduction program.

As the models have been verified and post-audited with 12 years of data in the case of Lake Ontario and with 16 years of data in the case of Lake Erie, the application of these models for operational use is justified and has been carried out. For future projections, estimates of the lake responses to further management strategies can be obtained from the scenario results presented or from a more refined run.

ACKNOWLEDGEMENTS

The authors wish to acknowledge constructive comments given by D.C.L. Lam on aspects of the report. Computer programs developed by B. Hansen and J. Gurnell and total phosphorus loading values supplied by A. Fraser are appreciated.

REFERENCES

Burns, N.M. and C. Ross, 1972. 'Project Hypo'. Canada Centre for Inland Waters, Burlington, Ontario, Canada, Paper No. 6, 180 p.

Charlton, M.N. 1980. Oxygen depletion in Lake Erie: Has there been any change? Can. J. Fish. Aquat. Sci. 37:72-81.

Fraser, A.S. and K.E. Willson. 1981. Loading estimates to Lake Erie, 1967-1976. IWD Scientific Series No. 120. Ottawa, Ontario, 23 pp.

International Joint Commission, 1978. Great Lakes Water Quality Agreement between the United States of America and Canada, IJC, Windsor, Ontario, 56 p.

Lam, D.C.L. and B. Hanson. 1983. Implementation of an operational water quality model in an interactive graphics environment. A Users' Manual. NWRI Report, Burlington, Ont., 13 p.

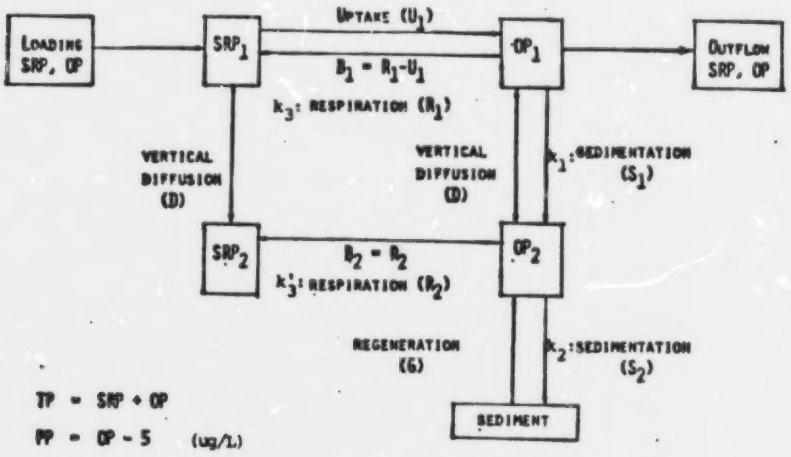
Lam, D.C.L., W.M. Schertzer and A.S. Fraser. 1983. Simulation of Lake Erie water quality responses to loading and weather variations. IWD Scientific Series No. 134, National Water Research Institute, Canada Centre for Inland Waters, Burlington.

Lam, D.C.L. and W.M. Schertzer. 1984. Application of integrated physics-biochemistry to Lake Erie water quality management problems. (Unpublished Manuscript). NWRI, Burlington, Ontario.

Neilson, M. and R. Stevens. 1983. Lake Ontario total phosphorus, soluble reactive phosphorus and organic phosphorus concentrations from 1967 to 1983. (Unpublished manuscript). Water Quality Branch, Ontario Region, 5 pp.

Simons, T.J. 1979. Assessment of water quality simulation capability for Lake Ontario. IWD Scientific Series No. 111, National Water Research Institute, Canada Centre for Inland Waters, Burlington, 220 pp.

1a) LAKE ONTARIO WATER QUALITY MODEL



1b) LAKE ERIE WATER QUALITY MODEL

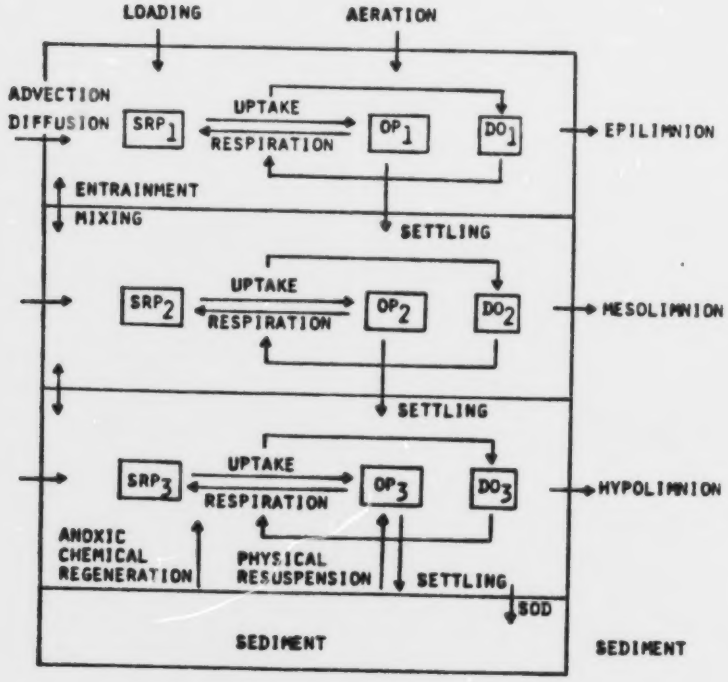
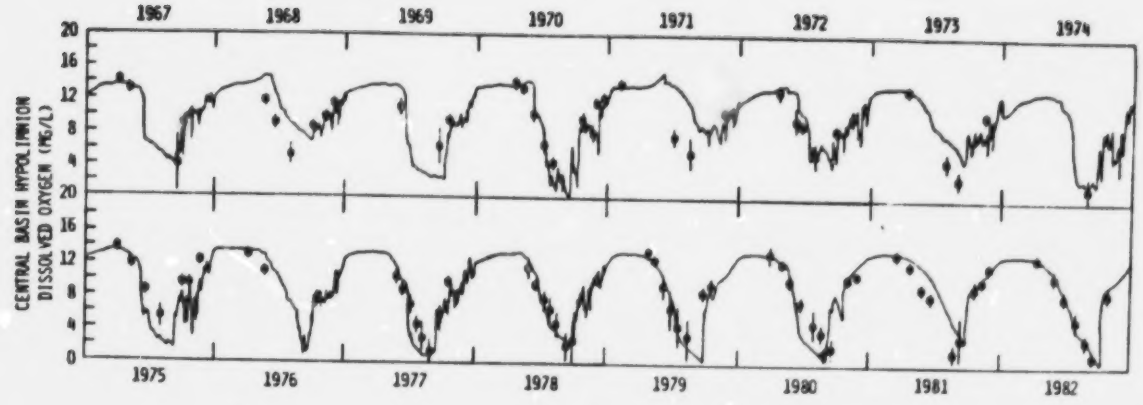


Figure 1 Schematic representation of the Lake Ontario (2-layer ; 2-component) and the Lake Erie (3-layer ; 3-component) Water Quality Models.

2a)



2b)

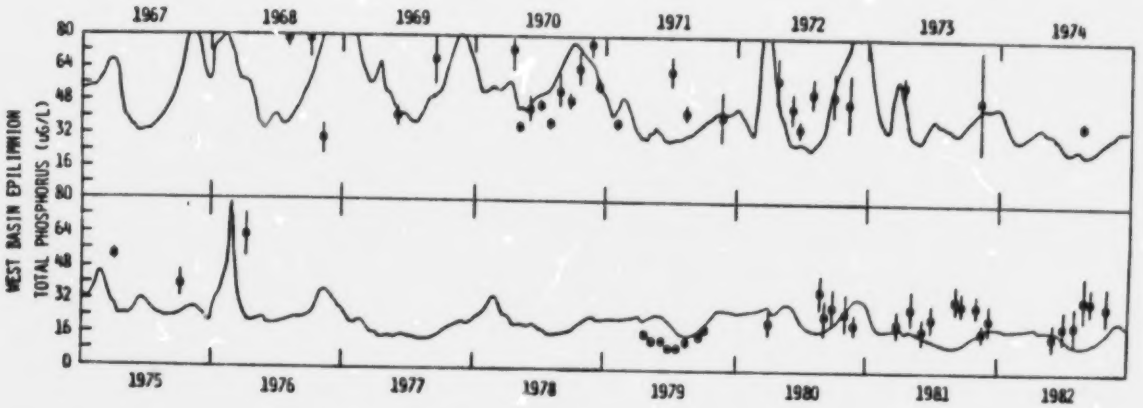


Figure 2a Comparison of computed (——) and observed (—■—) dissolved oxygen for the Central Basin hypolimnion of Lake Erie from 1967 to 1982.

2b Comparison of computed (——) and observed (—■—) total phosphorus concentration for the West Basin of Lake Erie from 1967 to 1982.

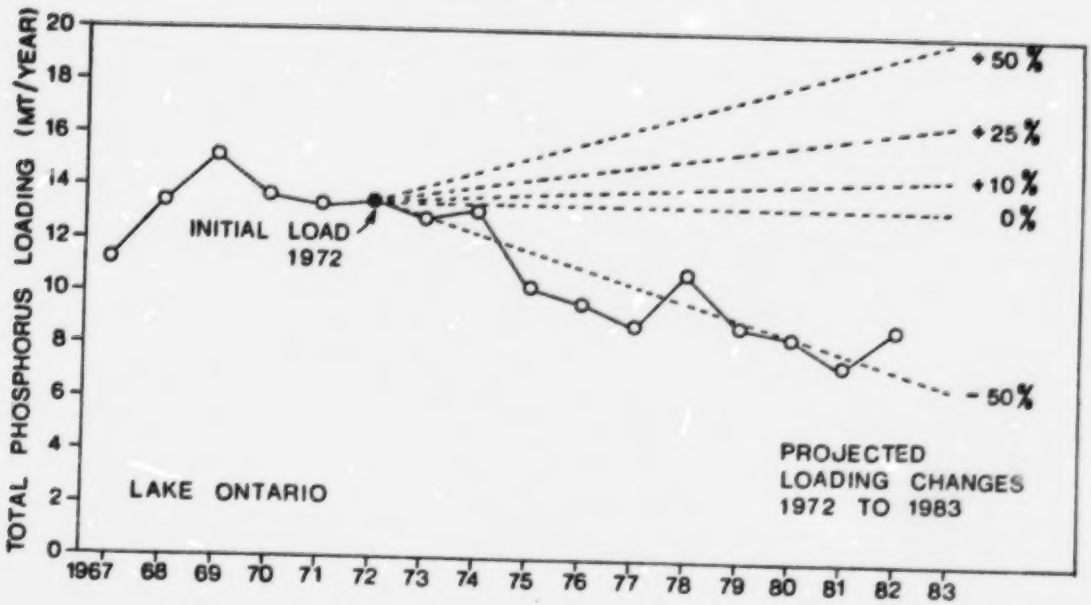


Figure 3 Actual total phosphorus loading to Lake Ontario (O) from 1967 to 1983 and illustration of various total phosphorus loading senarios (----) from 1972 to 1983.

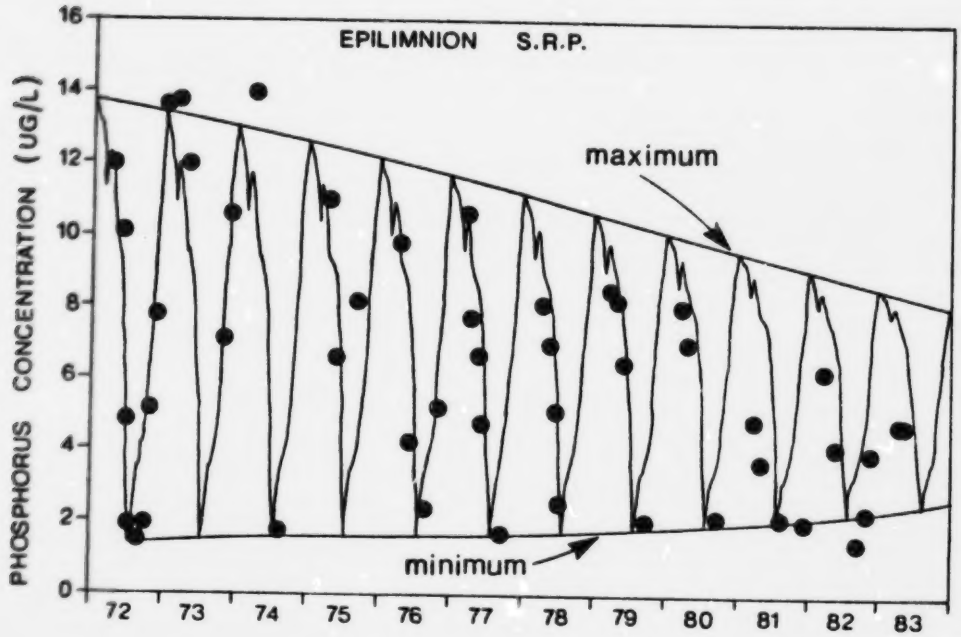


Figure 4 Application of the Lake Ontario operational water quality model to simulate seasonal epilimnion soluble reactive phosphorus concentrations (——) and comparison of results with observations (●) in the period 1972 to 1983.

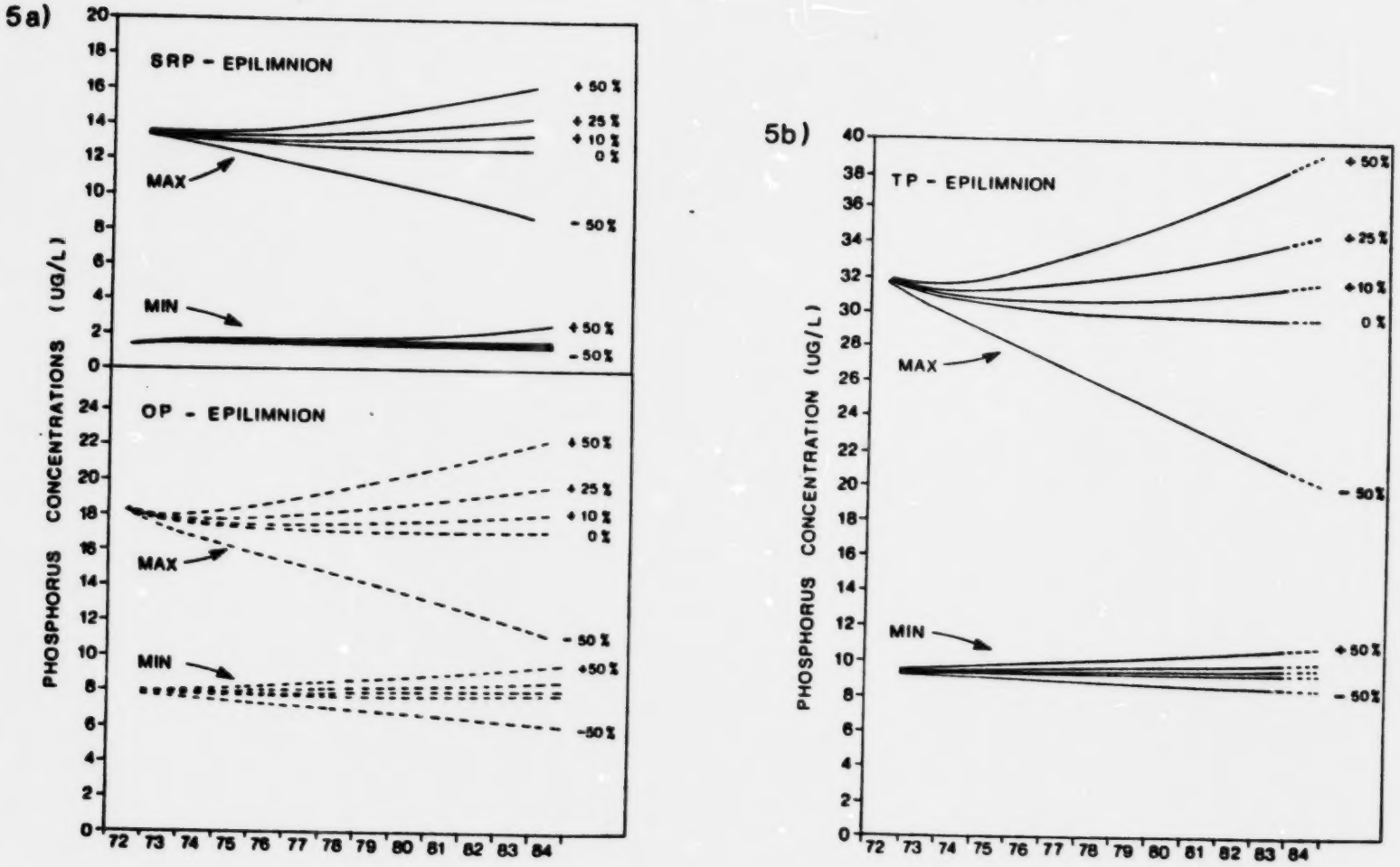


Figure 5 Maximun and minimum trends in computed epilimnion SRP, OP, and TP concentrations for various total phosphorus loading senarios in Lake Ontario from 1972 to 1983.

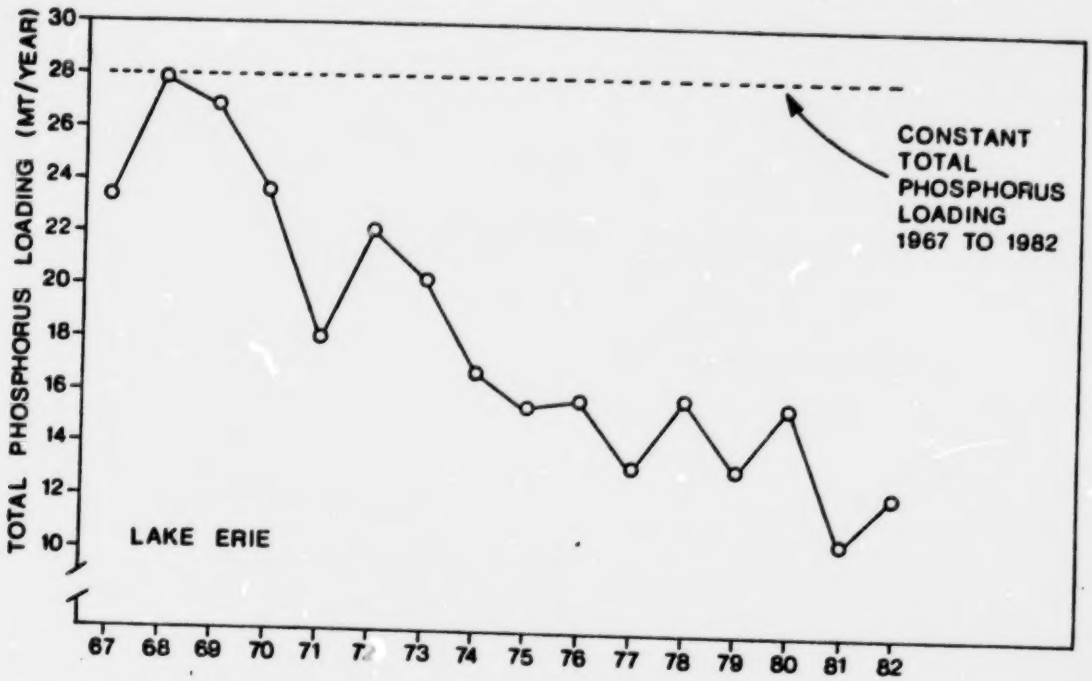


Figure 6 Actual total phosphorus loading to Lake Erie (O) from 1967 to 1982 and illustration of a high constant total phosphorus loading senario (----).

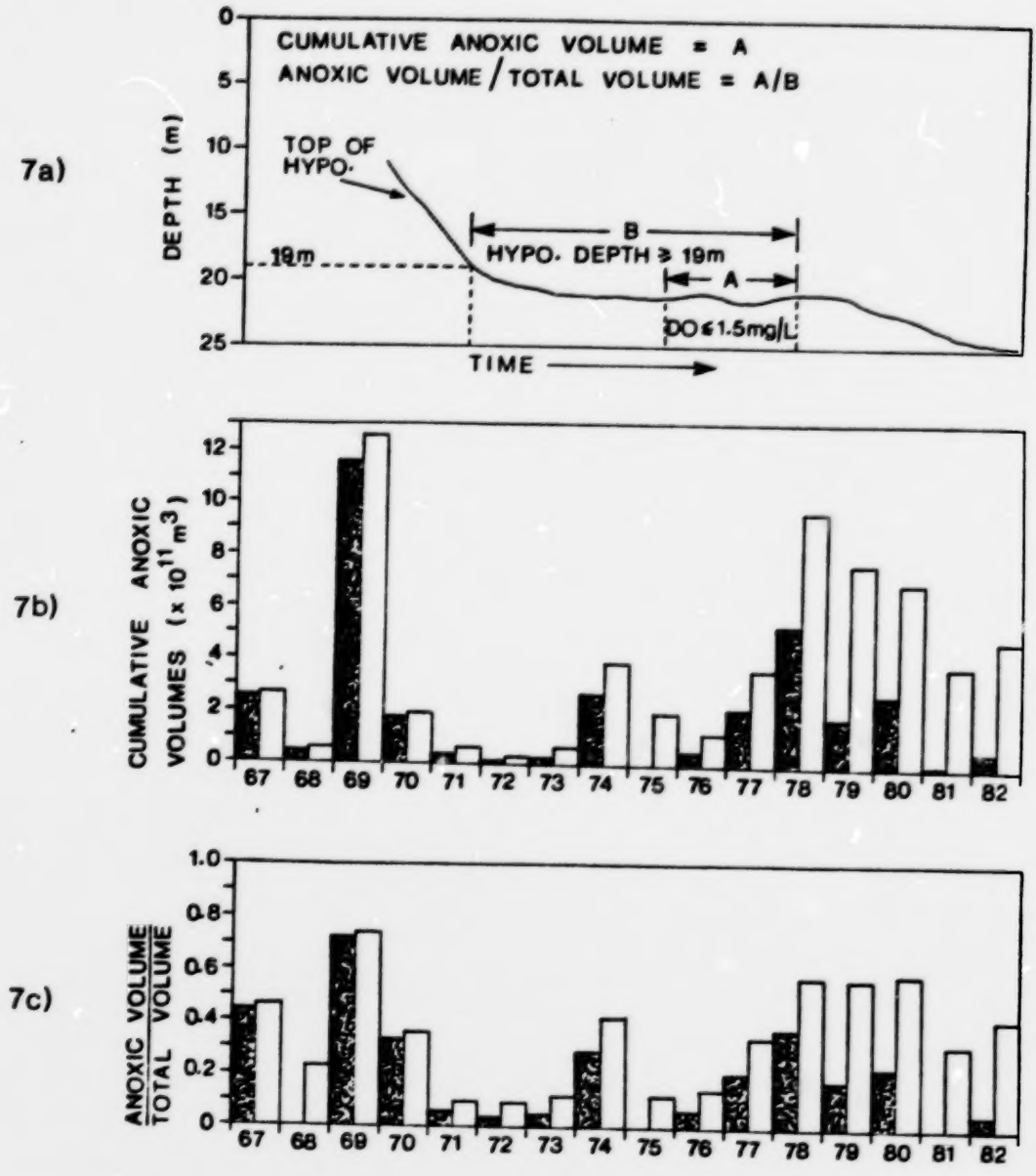


Figure 7 Comparison of the 'prevalence' of Lake Erie Central Basin anoxia from 1967 to 1982 for simulations using the actual total phosphorus loading (shading) and for a high total phosphorus loading senario (no shading). Figure 7a is a schematic representation of the integration of meteorological effects (simulated hypolimnion depth) with chemical processes (simulated dissolved oxygen concentration) to derive an index to illustrate the 'prevalence' of anoxia using, (b) cumulative anoxic volumes and (b) the ratio between computed anoxic volumes and the total volume.